Obstacle stepping in patients with Parkinson's disease: complexity does influence performance

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Abstract Patients with Parkinson's disease (PD) have difficulties in performing complex bimanual movements. Here we have examined acquisition and performance of a bilateral obstacle stepping task to see whether these difficulties are also present during bipedal movements. Subjects had to minimize foot clearance when repeatedly stepping on a treadmill over randomly approaching obstacles on either side. The subjects had full vision and received acoustic feedback information about task performance. Foot clearance improved in healthy and PD subjects during the acquisition of the task. However, PD subjects showed a slower improvement and achieved a poorer performance level. Thus, in contrast to unilateral obstacle stepping, where no deficits in performance after task repetition were found in PD subjects, bilateral obstacle stepping was poorer in these subjects compared to healthy subjects. The present results extend findings from upper to lower limb movements, namely that PD subjects have difficulties in the performance of bilateral motor tasks.

Key words Parkinson's disease · bilateral obstacle stepping · motor learning · motor performance

Introduction

Parkinson's disease (PD) is characterized by deficits in motor control, such as difficulties in movement initiation [22], scaling movement amplitudes [10] or modulating muscle activity [6, 21]. Movement performance was shown to strongly deteriorate with increasing complexity in upper limb movements [11]. Furthermore, an increased movement time and variability as well as decreased movement velocity occur in bilateral arm and finger movements [13, 25].

PD subjects also have difficulties in gait initiation [12, 22], adapting to disturbances [23], and they walk with short strides and fall frequently in advanced disease stages [2]. In a previous study the acquisition and performance of unilateral obstacle stepping was evaluated in PD patients [32]. Patients' performance was initially poorer and improved more slowly than healthy subjects. However, after task repetition the performance became similar in both groups.

In upper limb studies [13, 25], PD subjects experienced greater difficulties in the performance of complex bilateral tasks compared to healthy subjects. Therefore, it was of interest to evaluate to what extent a more complex lower limb locomotor task, i.e., bilateral obstacle stepping, reveals stronger deficits. Such a task requires major demands on the interaction between anticipatory postural adjustments and voluntary control of leg movements. A defective coordination of upper and lower limbs [27, 34] combined with abnormal postural reactions [24] might lead to larger problems in the performance of the bilateral compared to the unilateral obstacle stepping task. Furthermore, an impaired use of feedback information [33] in connection with a reduced kinaesthetic sensation [4] might also negatively influence the more complex task performance.

Therefore, the aim of this study was to investigate the

acquisition and performance of a more complex bilateral obstacle stepping task compared to unilateral obstacle stepping in PD patients and healthy age-matched control subjects. On the basis of previous studies looking at the performance of bimanual tasks in PD patients, we hypothesized that a poorer acquisition and performance in these subjects would be seen compared to unilateral obstacle stepping and healthy subjects.

Methods

The study was approved by the Cantonal Ethics Commission and conformed to standards set by the Declaration of Helsinki. The subjects were informed about the experiments and gave written consent. Seventeen patients with PD (4 females, for detail see Table 1) and 15 age-matched healthy subjects (5 females) participated. Inclusion criteria for the patients were the diagnosis of idiopathic PD according to the UK Parkinson's disease Brain Bank criteria and Hoehn and Yahr (HY) stages 1.5–3. Only subjects who were able to walk unassisted on the treadmill at a speed of 2.5 km/h were included [cf. 32]. In addition, before starting the experiment, the subjects performed three test trials in order to determine their ability to perform the obstacle stepping task. Five of the seventeen PD subjects were not able to walk with freely moving arms on the treadmill and performed the experiment while holding on to the parallel bars. The data of these subjects were included into the analysis.

Subjects with other associated neurological, cardiovascular, orthopedic, and psychiatric diagnoses as well as those with L-dopa induced hallucinations were excluded. Furthermore, the PD patients performed the "Mini Mental State Examination" (MMSE) in order to exclude a major cognitive deficit (mean result: 29.47 ± 0.92; maximum possible: 30).

The average age of the PD patients was 62.7 years (standard deviation (SD) = 8.4). They weighed 79.7 kg (SD = 19.9) and were 174 cm (SD = 8.5) tall. The healthy subjects had an average age of 63.1 years (SD = 9.2), weighed 68.4 kg (SD = 11.9) and were 170 cm (SD = 6.9) tall. There was no statistical difference between the two subject groups ($P \geq 0.065$). Patients were tested 1–2 hours after taking medication (i.e., during their best *on* state).

General procedures and data recordings

Subjects walked on a treadmill (Woodway, Weil am Rhein, Germany) with a speed of 2.5 km/h and freely moving arms (Fig. 1). The subjects were suspended from a parachute harness throughout the experiment to maintain safety. Two custom-built obstacle machines were placed next to the treadmill (ALEA Solutions GmbH, Zurich, Switzerland), i.e., one for the right and one for the left leg, in order to study the bilateral obstacle stepping. The obstacles consisted of a foam stick, fixed 14 cm above the treadmill, which were attached to the obstacle machine such that they folded back upon touch. The heel strike of the particular foot, measured by force sensors underneath the treadmill, was used as a trigger to randomly start the movement of the corresponding obstacle with a randomized time interval that varied between 2 and 11 seconds. Thus, the subjects were not able to predict when an approaching obstacle would appear, or which side the obstacle would approach from. After release, the obstacle moved at the same speed as the treadmill and the subject could step over the obstacle without changing the rhythmic walking cadence. After subjects had stepped over the obstacle, it folded up at the end of the treadmill and returned to its start position.

The learning task consisted of repetitively stepping over the obstacles. The subjects were instructed to minimize the distance between foot and obstacle (foot clearance), according to an acoustic feedback signal provided by earphones. Foot clearance was determined by an infrared system attached to the obstacle machine. During an obstacle step, the crossing leg passed through the infrared beam and foot clearance was measured with an accuracy of 1 mm.

The acoustic feedback was defined in 2-cm intervals between 0

Table 1 Characteristics of patients with Parkinson's disease

Sex	Age (y)	mHY	Duration of PD (y)	UPDRS (III)	UPDRS (I-IV)	Dyskinesias	LED	Medication
M	68	2.5	10	28	40	X	780	600 mg L-dopa retard
M	64	2	1	16	19	○	300	9 mg ropinirole
F	72	2.5	9	18	28	X	1340	800 mg L-dopa retard, 3 mg pramipexole
F	62	2.5	9	13	22	X	852	400 mg L-dopa retard, 400 mg L-dopa
M	80	2.5	6	32	40	○	1040	800 mg L-dopa retard
M	62	2.5	3	18	31	○	930	600 mg L-dopa retard, 1.5 mg pramipexole
F	52	2.5	9	28	40	X	698	600 mg L-dopa (+ entacapone)
M	63	2.5	7	19	36	○	699	300 mg L-dopa (+ entacapone), 4.5 mg pergolide
F	68	3	18	26	33	X	237	150 mg L-dopa (+ entacapone), 1.125 mg pramipexole
M	54	2	11	21	33	X	1131	800 mg L-dopa (+ entacapone), 14 mg ropinirole 800
M	57	2.5	11	42	58	○	1140	800 mg L-dopa retard, 4 mg pramipexole
M	70	2.5	6	40	53	○	1633	1000 mg L-dopa retard, 10 mg ropinirole
M	69	2.5	4	27	35	○	1280	600 mg L-dopa retard, 15 mg ropinirole
M	47	2	4	17	30	X	690	800 mg L-dopa (+ entacapone), 0.4 mg cabergoline
M	65	2.5	10	23	37	X	1280	900 mg L-dopa (+ entacapone), 16 mg ropinirole
M	54	2.5	7	14	20	X	932	400 mg L-dopa (+ entacapone), 14 mg ropinirole
M	60	2.5	4	14	18	○	200	6 mg ropinirole
Mean	**62.7**	**2.4**	**7.6**	**23.3**	**33.8**		**910**	

F Female; *M* Male; *PD* Parkinson's disease; *mHY* modified Hoehn and Yahr scale; *UPDRS* Unified Parkinson Disease Rating Scale; *UPDRS III* Motor examination of UPDRS; *LED* Levodopa equivalent doses

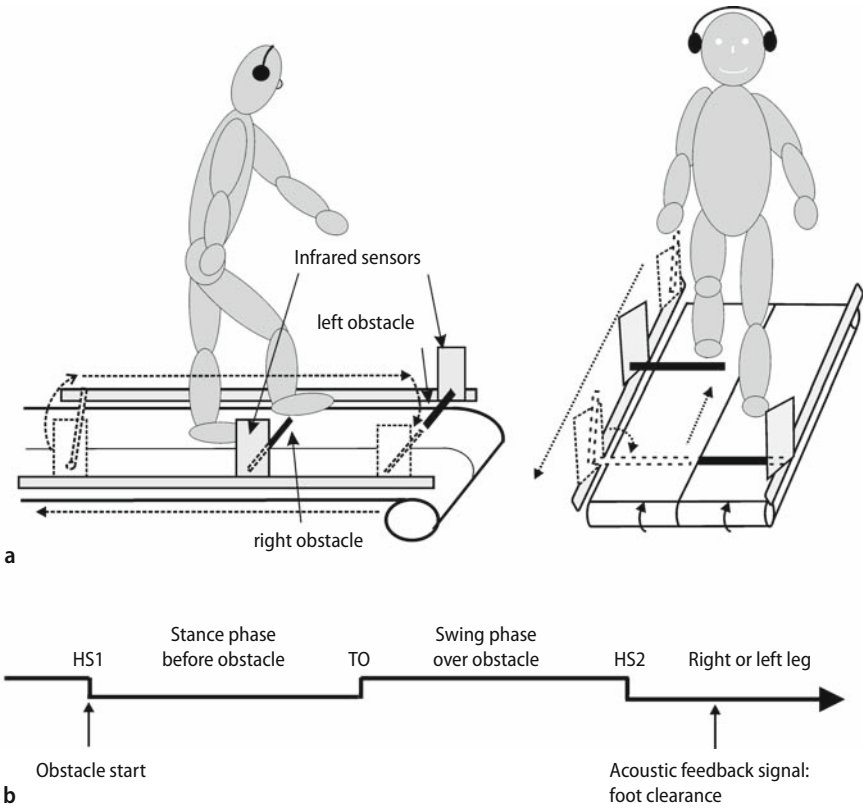

Fig. 1 Experimental setup. **a** Schematic experimental set-up illustrating a subject stepping over the obstacle with the right (or left) leading leg and free moving arms. Either the left or the right obstacle was randomly released, moving at the same speed as the treadmill belt, with a randomized time interval. The level of foot clearance was determined by infrared sensors attached to the obstacle machine. **b** Timing of events during a single obstacle step. At heel strike (HS1) the obstacle was started. The swing phase over the obstacle lasted from toe off (TO) to HS2. After the leg had successfully swung over the obstacle, an acoustic feedback signal was provided to indicate foot clearance

and 12 cm. A higher foot clearance was signaled by a higher pitched feedback tone. At the lowest level (optimal foot clearance, i.e., between 0 and 2 cm) a double-beep of a 125 and 1000 Hz sinusoidal signal (600 ms duration) was provided. The other feedback signals consisted of a single beep (176, 250, 354, 500 or 707 Hz rectangular signal of 600 ms duration for the second lowest level to the highest level, respectively). Thus, subjects could use six different levels of acoustic feedback to minimize foot clearance.

A more pronounced learning profile has previously been observed when healthy subjects had reduced vision and acoustic feedback about foot clearance was provided [5, 31]. However, in a previous study it was shown that restricted vision strongly deteriorated the performance of PD subjects during unilateral obstacle stepping [32]. Therefore, in order to facilitate the performance, subjects had full vision and an additional acoustic feedback signal. The number of obstacle hits was recorded by the obstacle machine.

The whole experiment consisted of two blocks of trials, each consisting of 60 steps over the obstacles (i.e., 30 obstacle steps with each leg). Between the two blocks the subjects had a break of 5 to 10 minutes.

Data analysis

An improvement of performance during repetitive obstacle stepping was defined by: (1) a lower level of foot clearance, and (2) a decrease in the number of obstacle hits.

The course of foot clearance was analyzed for both blocks of trials by fitting a power function through the averaged data points of all subjects. One characteristic of a power function is that logarithmic transformation of both the number of trials and the performance results in a linear relationship ($y = b_0 + b_1 \times x$). The regression coefficient b_1 provides a quantification of the adaptive rate.

Mean onset and end values of the foot clearance were calculated by averaging the values of the first and last 4 steps for each subject and each block of trials [30].

Statistics

All statistical calculations were performed using a 2-way analysis of variance (ANOVA) for repeated measures. To determine differences in *foot clearance between onset and end* of each block, the measurements of the first and last 4 steps of all subjects were taken for analysis. The factors condition (4 levels: onset and end of the first and second block, respectively) and group (2 levels: PD and healthy subjects) and their interaction were included in the model.

Differences in the *course* of *foot clearance* between PD and healthy subjects were analyzed by calculating the adaptive rates for each subject separately. The factor group was similar in the 2-way ANOVA for repeated measures, while the factor block had now two levels: block 1 and 2. Pair-wise comparisons were performed using Student's t-tests, and the P-values were adjusted for multiple comparisons using Bonferroni's correction.

Finally, in the PD subjects, the Spearman's correlation coefficient (r_s) was calculated between clinical parameters (duration of PD, motor examination of the Unified Parkinson Disease Rating Scale [UPDRS III]) and the total percent improvement in foot clearance during both obstacle blocks and the number of obstacle hits.

Results

A separate analysis of the right and left leg of all subjects showed no difference between legs. Therefore, results obtained from both legs were pooled together.

Foot clearance data were removed when the subjects touched the obstacle (healthy subjects: block 1: n = 29, block 2: n = 31; PD subjects: block 1: n = 49, block 2: n = 36; for details see below).

Course of task performance

During the acquisition of the bilateral obstacle stepping task, the healthy subjects improved foot clearance faster than PD patients. Fig. 2 a shows the course of foot clearance for both groups during either block of trials quantified as the mean adaptive rate. Foot clearance improved more quickly during block 1 compared to block 2 ($F(1, 30) = 23.1$; $P < 0.001$; healthy subjects: $P = 0.003$; PD subjects: $P = 0.022$) as well as in healthy compared to PD subjects ($F(1, 30) = 13.83$; $P < 0.001$; block 1: $P = 0.008$; block 2: $P = 0.065$). In the healthy subjects, the individual adaptive rates ranged from –0.70 to –0.02 (SD = 0.18) during the first block and from –0.41 to –0.01 (SD = 0.12) during the second block. For the PD subjects, the corresponding range was from –0.39 to 0.14 (SD = 0.12) during the first block and from –0.31 to 0.10 (SD = 0.12) in the subsequent block.

During the obstacle steps, there was no difference in the swing phase duration between PD and healthy subjects (mean swing phase duration: PD subjects: 0.70 s, SD = 0.12; healthy subjects: 0.77 s, SD = 0.10; $P = 0.099$). In addition, no adaptation in swing phase duration occurred during both blocks of trials in the two groups (mean adaptive rate: PD subjects: AR = 0.01; healthy subjects: AR = 0.02).

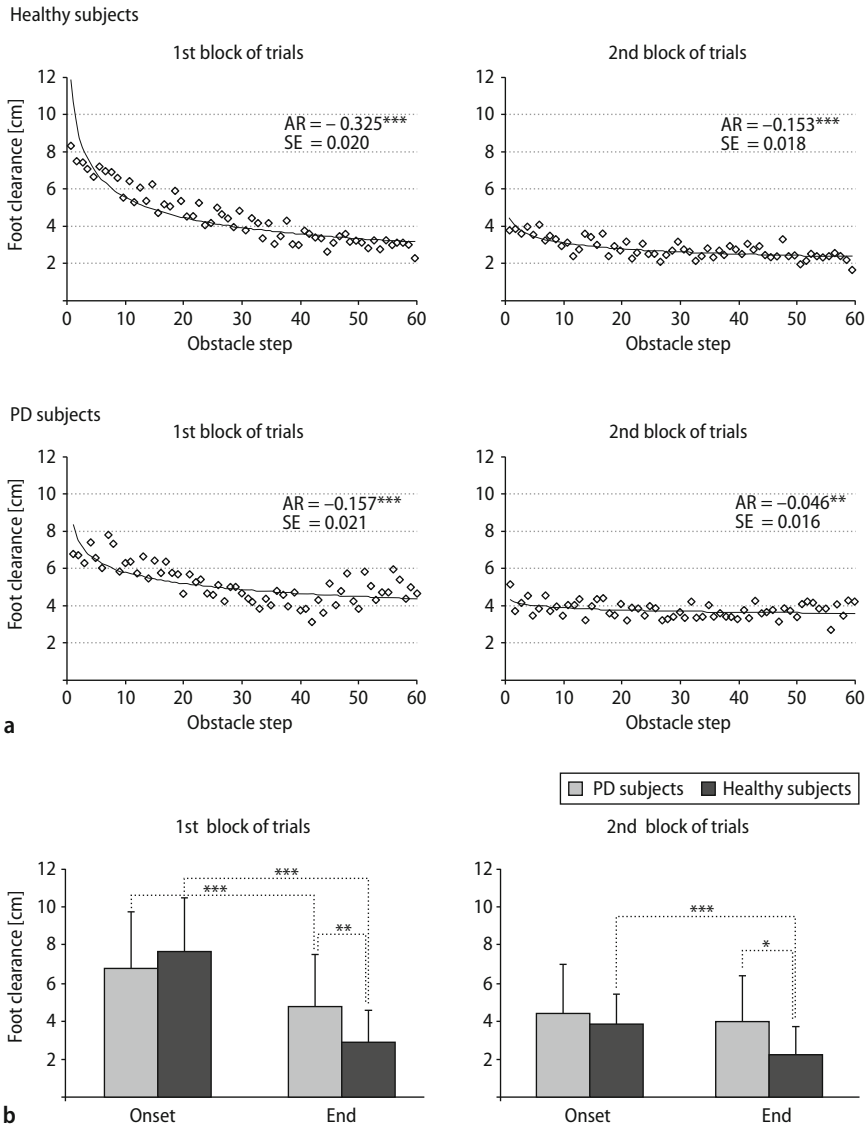

Fig. 2 Course of foot clearance. **a** Course of the averaged data of foot clearance for healthy subjects and the patients with Parkinson's disease (PD) for both blocks of trials. "Obstacle step" indicates the number of obstacle trials during each block. The adaptive rates are mean values of all subjects and showed a significant decrease (** $P < 0.01$, *** $P < 0.001$). Data of obstacle hits were removed. AR adaptive rate; SE standard error. **b** Onset and end values (mean and standard deviations) of the foot clearance calculated by averaging the values of the first and last 4 steps for each subject and each block of trials. Data of obstacle hits were removed. Significant differences are indicated by asterisks (* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$)

Onset and end values of foot clearance

The averaged foot clearance onset and end values differed between groups and conditions ($F(3, 90) = 11.43$, $P < 0.001$). Both subject groups started the experiment at the same level of foot clearance ($P = 1.0$; see Fig. 2 b), improved foot clearance significantly ($P < 0.001$). However, at the end of block 1, healthy subjects performed better than PD subjects ($P = 0.004$). Similarly, in block 2 (Fig. 2 b), the onset values were similar in both groups ($P = 1.0$), but only the healthy subjects improved foot clearance significantly ($P < 0.001$) and achieved lower end values compared to the PD subjects ($P = 0.02$).

Obstacle hits

The healthy subjects touched the obstacle on average of 3.9 times (SD = 1.5; range, 0–6) times during the first block and 2.1 times (SD = 1.8; range, 0–6) times during the second block. For the PD subjects, the number of obstacle hits were 2.9 (SD = 2.4; range, 0–11) during the first block and 2.1 (SD = 2.0; range, 0–8) during the second block. Repeated measures ANOVA showed no differences between the groups ($F(1, 30) = 0.60$; $P = 0.443$) or the blocks of trials ($F(1, 30) = 1.35$; $P = 0.255$) or the interaction ($F(1, 30) = 2.72$; $P = 0.109$).

Comparison to unilateral obstacle stepping

Additionally, the mean foot clearance onset and end values during the bilateral obstacle stepping task were compared with those during unilateral obstacle stepping obtained from a previous study [32]. During the latter task, subjects performed 50 steps over the obstacle. A previous study showed that acquisition of obstacle stepping can be transferred from one leg to the other [29]. Not surprisingly, we found no differences between the left and right leg. Therefore, we compared steps 1 to 4 and 47 to 50 of the first block of trials. Using a Mann Whitney U test (alpha was set to 0.025 to correct for two comparisons), we found a significantly lower foot clearance at the end ($p = 0.01$), but not at the onset ($p = 0.07$) during the unilateral task. Hence, performance improved more during the unilateral task compared to the bilateral task.

Clinical parameters and task performance

In the PD subjects, there was a significant correlation between the total number of obstacle hits and the motor examination of the UPDRS (UPDRS III; $r_s = 0.49$, $P < 0.05$). No correlation was found between the other individual clinical parameters and task performance: Between the number of obstacle hits and duration of PD, r_s amounted to 0.21 ($P = 0.41$); for the percent decrease in foot clearance, r_s amounted to 0.15 ($P = 0.56$; duration of PD) and 0.17 ($P = 0.53$; UPDRS III).

Discussion

The aim of this study was to evaluate the ability of PD patients to acquire and perform a high-precision bilateral locomotor task. A deterioration of performance from the unilateral to the bilateral obstacle task was expected, based on previous results of patients performing complex bilateral hand movements [13, 25]. The main observations were the following: (1) Foot clearance improved in the PD and healthy subjects during the acquisition of the task. However, improvement was slower and performance was poorer in PD subjects. (2) The healthy subjects tended to hit the obstacle less frequently compared to the PD subjects, although this was statistically not significant. (3) Compared to unilateral obstacle stepping, performance was slightly worse. (4) The number of obstacle hits correlated with the severity of the clinically assessed motor impairment, in this select group of mildly affected PD subjects.

Task performance

Task performance improved with repetition in both PD and healthy subjects. This suggests a motor learning in both groups. However, both the higher level of foot clearance at the end of the first block and the lower adaptive rate indicate that, in line with a previous report [32], performance improved slower in PD than in control subjects. Nevertheless, the improvement was less during bilateral compared to unilateral obstacle stepping [32]. This difference fits with studies on upper limbs indicating greater difficulties in complex bimanual motor task learning [13, 25]. Depending on the task investigated, it was suggested that a dysfunction of the basal ganglia resulted in a difficulty to switch between motor programs [11], to transfer acquired performance to different feedback conditions [33] or to synchronize the two limbs [13]. We suggest that the greater difficulty in the bilateral task can also be explained by an impairment in dividing attention between concurrent tasks, which plays a role in all bilateral tasks [1, 9, 25]. In addition, postural stability is known to be influenced by attention [16, 19]. This might have played a role here as subjects had to walk with freely moving arms. Compared to the previous study [32], an attentional deficit might have negatively influenced task improvement.

Furthermore, the reduction in external cueing could have contributed to the worse performance as the acoustic warning signal about the approaching obstacle (pro-

vided in the previous study [32]) was removed. Indeed, PD subjects perform externally triggered tasks better than internally generated ones [3, 7]. Finally, since subjects had to lower foot clearance according to different levels of an acoustic feedback tone, the task can be regarded as a movement scaling task, which is more difficult for PD subjects [10, 14, 26]. The poorer end performance in the present study supports these findings.

Some PD subjects were only able to perform the experiment by holding onto the parallel bars, leading to reduced balance demands. A separate examination revealed a similar improvement in foot clearance and number of obstacle hits compared to the PD subjects with freely moving arms.

Finally, the clinical parameter UPDRS III (motor examination) showed a correlation to the number of error trials during bilateral obstacle stepping (i.e., obstacle hits), but not to the improvement in task performance. This result suggests that this clinical score might at least partially be suitable to assess the ability of PD subjects to perform such a functionally demanding task as investigated in the present study.

Methodological limitations

Parts of the present task can be considered externally triggered (i.e. treadmill walking and the moving obstacle machine), which is known to positively influence task performance in PD subjects [8, 15, 20, 28]. Nevertheless, the number of external cues was minimized compared to a previous study [32] and improved walking performance acquired during treadmill walking can be transferred to the over-ground conditions [17, 18].

Furthermore, several factors necessarily limit the generalization of the results for natural walking conditions. The present task had to be assigned to laboratory conditions (fixed obstacle height, shape and consistency, homogeneous walking cadence), i.e., it reflects only partially complex locomotor behavior in daily life situations. Furthermore, the number of PD subjects was rather small and they suffered only mild motor impairment.

The subjects had to minimize their foot clearance according to an acoustic feedback signal. Therefore, difficulties in discriminating between the different beeps might have negatively influenced task performance. However, as PD subjects with emerging dementia and with other neurological deficits were not included in the study, such difficulties seem rather unlikely. In addition, the same acoustic feedback signals were used during unilateral obstacle stepping [32] and the present results were compared with these experiments.

Conclusions

The present findings support the hypothesis that patients with mild to moderate PD suffer from an impaired acquisition and performance of a high-precision locomotor task, such as bilateral obstacle stepping. During task repetition, improvement is slower and performance level is poorer in PD subjects compared to healthy subjects. However, PD subjects were able to improve their performance during the course of the experiment to some extent. We suggest that the present results extend findings from upper to lower limb movement tasks, namely that performance is worse in PD compared to control subjects in bilateral compared to unilateral tasks. We assume that walking with freely moving arms over obstacles approaching on both sides resembles natural movements. Therefore, the results support the suggestion that PD subjects suffer from greater difficulties in daily life situations due to difficulties in locomotor behavior when attention has to be shared. However, adequate training can improve their adaptive locomotor behavior. Further research should be directed towards exploring anticipatory behavior (and timing of stepping response) during obstacle stepping, associated with incidences of falls in PD patients.

Conflict of interest The authors declare no conflict of interest.

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